Next-to-leading order QCD corrections to $t\bar{t}\gamma$ production at the 7 TeV LHC

Duan Peng-Fei, Zhang Ren-You, Ma Wen-Gan,
Han Liang, Guo Lei, and Wang Shao-Ming
Department of Modern Physics, University of Science and Technology
of China (USTC), Hefei, Anhui 230026, P.R.China

We present the theoretical predictions including the complete next-to-leading order (NLO) QCD corrections to the top-quark pair production in association with a photon at the LHC with center-of-mass system energy of 7 TeV. The uncertainties of the leading order (LO) and NLO QCD corrected cross sections due to the renormalization/factorization scale, and the distributions of the transverse momenta of final top-quark and photon are studied. Moreover, we provide the numerical results of the LO, NLO QCD corrected cross sections and the corresponding K-factors with different photon transverse momentum cuts. We also discuss the impact of QCD corrections to the $pp \to t\bar{t}\gamma + X$ in case of there existing the exotic top-quark with an electric charge of $-4e/3$ at the 7 TeV LHC.

PACS numbers: 14.65.Ha, 14.70.Bh, 12.38.Bx

Since the discovery of top-quark at the Fermilab in 1995[1, 2], it has opened up a new research field of top physics, not only because top-quark breaks the electroweak symmetry maximally as the heaviest elementary fermion discovered up to now, but also due to the lack of precise measurement of its properties. In particular, the couplings of the top-quark to the electroweak gauge bosons have not yet been precisely measured, which may turn out to be our first clue of new physics connected with the electroweak symmetry breaking (EWSB). Moreover, many properties of the particle are still poorly known, for example, the electric charge of top-quark, a fundamental quantity characterizing the electromagnetic interaction between the top-quark and photon, has not yet been experimentally determined. If we assume that the electric charge of the top-quark is $q_t = -4e/3$, instead of the normal value $q_t = 2e/3$, a consistent description of the top physics could still be obtained[3, 4]. As suggested by Ref.[5], studying the production of a top-quark pair in association with a hard photon is a more effective way to determine the top-quark charge.

Topics of higher order corrections to the top-quark pair production in various configurations at hadron colliders are the focus all the time. As early as late 1980's, the works studying the NLO QCD corrections to $t\bar{t}$ production [6] have been presented. Recently there has been significant progress in higher order corrections to $t\bar{t}$ production[7–9]. NLO QCD corrections are also known for the associated production processes involving top-pair production, including $t\bar{t}H$[10], $t\bar{t}j$ [11], $t\bar{t}Z$ [12] and $t\bar{t}\gamma$ [13, 14]. Since March 2010 the LHC has begun to run for the first attempt at 7 TeV. It will continue to operate in 7 TeV pp collision mode for some years. Now all the detectors are recording data, and both the ATLAS and CMS groups are launching the physics program at the colliding energy of 7 TeV.

Recently, Prof. Ivor Fleck in ATLAS experimental group suggested us to extend our NLO QCD calculations for the $pp \to t\bar{t}\gamma + X$ process to the 7 TeV LHC, and study the impact of the top-quark electric charge of $q_t = -4e/3$. He thought that will be helpful for their experimental data analyses[15]. In this report we calculate the NLO QCD corrections to the process $pp \to t\bar{t}\gamma + X$ at the 7 TeV LHC with different photon transverse momentum cuts, and studied their uncertainties induced by the factorization/renormalization scale, and the effects to the observables for $pp \to t\bar{t}\gamma + X$ process in case of there existing the exotic top-quark with an electric charge of $q_t = -4e/3$. In the paper of Ref.[13] we presented the detail calculations of the NLO QCD corrections to the associated production of $t\bar{t}\gamma$ at hadron colliders, and presented the results only for the Tevatron Run II and the 14 TeV LHC, but not for the 7 TeV LHC.

At the leading order (LO), hadronic $t\bar{t}\gamma$ production proceeds via $q - \bar{q}$ ($q = u, d, c, s$) annihilation and gluon-gluon fusion. The NLO QCD corrections to the $pp \to t\bar{t}\gamma + X$ process contain real and virtual corrections. The Feynman diagrams have been generated by FeynArts3.4[16] automatically, and the Feynman amplitudes are subsequently reduced by FormCalc5.4[17] programs. The calculations are carried out by adopting the dimensional regularization method to regularize the UV and IR divergences and implying the modified minimal subtraction ($\overline{\rm MS}$) scheme to renormalize the strong coupling constant and the relevant masses and fields except for the top-quark and gluon, whose masses and wave functions are renormalized by applying the on-shell scheme. After renormalization proce-

dure, the virtual correction is UV-finite. The IR divergences from the one-loop diagrams will be cancelled by adding the soft real gluon/light-quark emission corrections by using the two cutoff phase space slicing method (TCPSS)[18]. The remaining collinear divergences can be absorbed into the parton distribution functions(PDFs).

We take one-loop and two-loop running α_s in the LO and NLO calculations, respectively[19], with the number of active flavors $N_f = 5$, the QCD parameters $\Lambda_5^{LO} = 165$ MeV and $\Lambda_5^{\overline{MS}} = 226$ MeV in the LO and NLO calculations, respectively. The factorization scale and the renormalization scale are set to be equal for simplification (i.e., $\mu = \mu_f = \mu_r$) and $\mu = \mu_0 = m_t$ by default unless otherwise stated. In the numerical calculations, we take $m_t = 171.2$ GeV and $\alpha(m_Z)^{-1} = 127.918$[19]. It has been verified that the total cross section including the NLO QCD corrections is independent of the cutoffs δ_s and δ_c in adopting the TCPSS method, which has been shown in Figs.7(a,b) of Ref.[13]. In the following calculations, we fix the soft cutoff as $\delta_s = 10^{-4}$ and collinear cutoff as $\delta_c = \delta_s/50$. The calculations are carried out at the LHC with pp colliding energy $\sqrt{s} = 7$ TeV. A photon transverse momentum cut, $p_{T,cut}^{(\gamma)}$, is introduced, and the radiated photon is required to be relatively hard enough to fulfill the condition of $p_T^{(\gamma)} > p_{T,cut}^{(\gamma)}$. In real emission processes, we use the photon isolation cut to separate photon from the emitted jet[20]. The events are rejected unless they fulfills the condition of

$$\sum_i E_{T_i}\theta(\delta - R_{i\gamma}) \leq E_{T_\gamma}\frac{1-\cos\delta}{1-\cos\delta_0} \quad (\text{for all } \delta \leq \delta_0), \tag{1}$$

where E_{T_i} is the transverse energy of parton i, E_{T_γ} is the transverse energy of the photon, δ_0 is a fixed separation parameter that we set to be 0.4 in this work, and $R_{i\gamma}$ is the angular distance between parton i and the photon defined as

$$R_{i\gamma} = \sqrt{(\eta_i - \eta_\gamma)^2 + (\varphi_i - \varphi_\gamma)^2}, \tag{2}$$

where η and φ are the pseudorapidity and azimuthal angle respectively.

The LO and NLO cross sections for $t\bar{t}\gamma$ production at the LHC as the functions of the renormalization and factorization scale μ are plotted in Fig.1(a). The corresponding K-factor [$K \equiv \sigma_{NLO}/\sigma_{LO}$] is plotted in Fig.1(b). In Fig.1(a) and Fig.1(b), we take $p_T^{(\gamma)} > 10$ GeV, $q_t = 2e/3$, and the colliding energy in the proton-proton center-of-mass system as $\sqrt{s} = 7$ TeV. As shown in the figures the curve for the NLO cross section is much less sensitive to μ than the one for the

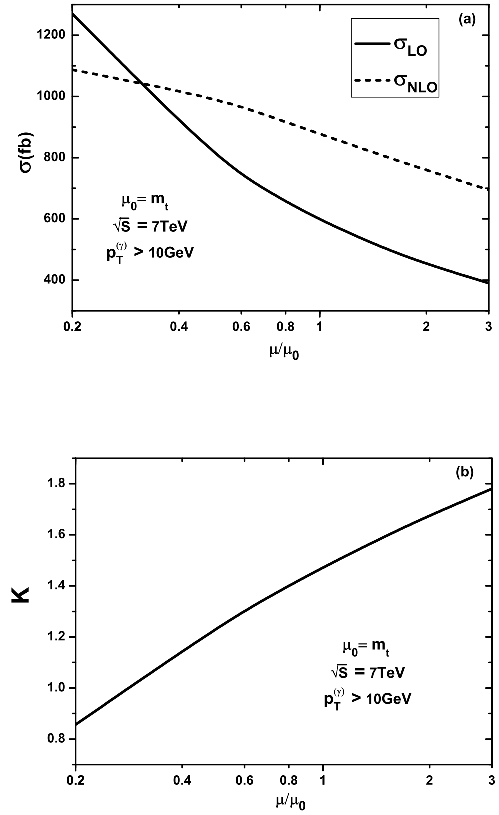

FIG. 1: (a) The dependence of the LO and NLO cross sections on the factorization/renormalization scale at the 7 TeV LHC. (b) The corresponding NLO QCD K-factor [$K \equiv \sigma_{NLO}/\sigma_{LO}$] versus the energy scale.

LO cross section, which indicates that the NLO QCD correction has obviously reduced the uncertainty of the cross section on the introduced parameter μ in the plotted range of μ/μ_0.

The LO and NLO distributions of the transverse momenta for the normal top-quark (with electric charge $2e/3$) and exotic top-quark (with electric charge $-4e/3$) at the LHC, are depicted in Fig.2(a) and Fig.2(b), respectively. The LO and NLO distributions of the transverse momenta for the photon with different top-quark electric charge ($2e/3$ or $-4e/3$) are depicted in Fig.3(a) and Fig.3(b), respectively. Figs.2 and 3 demonstrate that the NLO QCD corrections enhance significantly the distributions of $p_T^{(t)}$ and $p_T^{(\gamma)}$ for both the normal top-quark and the exotic top-quark. From the distributions of $p_T^{(\gamma)}$ in both Fig.3(a) and Fig.3(b), we conclude that most of the photons in the events of

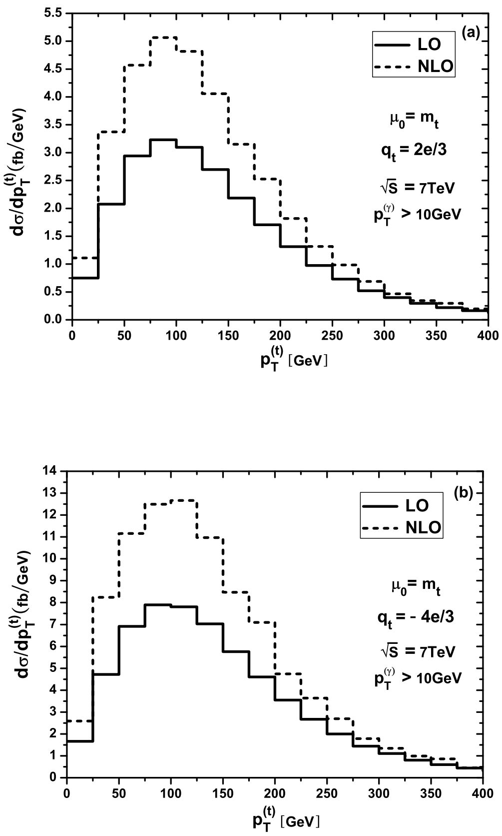

FIG. 2: (a) The LO and NLO distributions of the transverse momentum of the normal top-quark with $q_t = 2e/3$. (b) the LO and NLO distributions of the transverse momentum of the exotic top-quark with $q_t = -4e/3$, $\mu = m_t$, $p_T^{(\gamma)} > 10$ GeV and $\sqrt{s} = 7$ TeV.

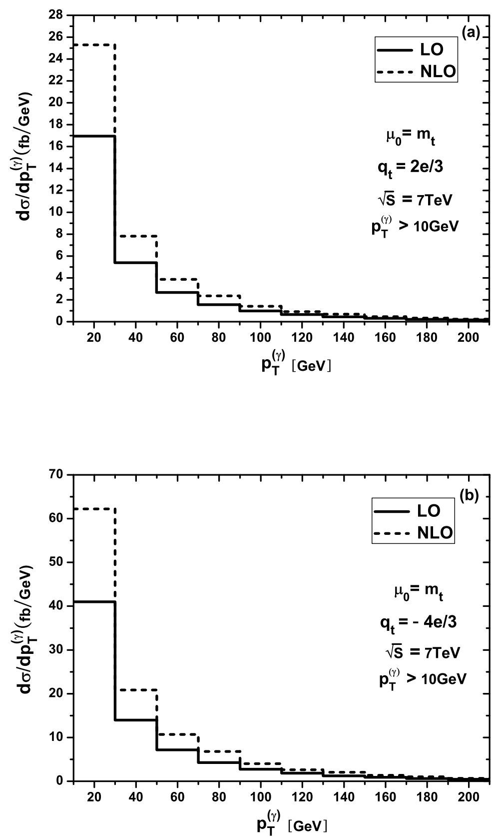

FIG. 3: The LO and NLO distributions of the transverse momentum of the photon at LHC with $\mu = m_t$, $p_T^{(\gamma)} > 10$ GeV and $\sqrt{s} = 7$ TeV. (a) top-quark with electric charge $q_t = 2e/3$. (b) top-quark with electric charge $q_t = -4e/3$.

$pp \to t\bar{t}\gamma + X$ are produced in low transverse momentum range at the LHC.

Now we study the impacts of the photon transverse momentum cut $p_{T,cut}^{(\gamma)}$ and the exiotic top-quark electric charge q_t on the cross section and K-factor. We calculate the LO and NLO cross sections and the corresponding K-factor [$K \equiv \sigma_{NLO}/\sigma_{LO}$] with $\mu = m_t$, $\sqrt{s} = 7$ TeV, $p_T^{(\gamma)} > 10$ GeV (or 15 GeV) and $q_t = 2e/3$ (or $-4e/3$). The numerical results are presented in Table I. Our numerical results turn out that the K-factor varies only slightly with the variation of either the photon transverse momentum cut or the top-quark electric charge (about 3% for the latter), although the LO and NLO cross sections strongly depend on the photon transverse momentum cut and the top-quark electric charge. We know that if the photon is merely radiated from the top-quarks, the cross section for $pp \to t\bar{t}\gamma + X$ production would be proportional to the square of the top-quark electric charge, which implies that the cross section with top-quark electric charge $q_t = -4e/3$ would be four times of that with top-quark electric charge $q_t = 2e/3$. Actually, both the LO and the NLO Feynman graphs include the diagrams with photon radiating from light-quark respectively, which makes the total cross sections in the exotic top-quark case less than three times of that in the normal top-quark case.

In summary, the calculations for the top-pair production associated with a photon at the 7 TeV LHC have been performed with the complete NLO QCD corrections. We investigate the dependence of the LO and NLO QCD corrected integrated cross sections on the factorization/renormalization energy scale. We present

	σ_{LO}(fb)	σ_{NLO}(fb)	K
$p_T^{(\gamma)} > 10$ GeV, $q_t = 2e/3$	596.0(2)	878(2)	1.4732
$p_T^{(\gamma)} > 10$ GeV, $q_t = -4e/3$	1513(1)	2276(5)	1.5043
$p_T^{(\gamma)} > 15$ GeV, $q_t = 2e/3$	454.6(2)	668(2)	1.4694
$p_T^{(\gamma)} > 15$ GeV, $q_t = -4e/3$	1179(1)	1775(5)	1.5055

TABLE I: The LO and NLO cross sections and the corresponding NLO QCD K-factor [$K \equiv \sigma_{NLO}/\sigma_{LO}$] with $\mu = m_t$, $\sqrt{s} = 7$ TeV and different values of photon transverse momentum cut $p_{T,cut}^{(\gamma)}$ and top-quark electric charge q_t.

predictions for the LO and NLO differential and integrated cross sections at the 7 TeV LHC in the cases of top-quark with $q_t = 2e/3$ and $-4e/3$. We demonstrate that the uncertainty of the LO cross section caused by the introduced energy scale μ is significantly improved by including the NLO QCD corrections. We study also the effects of different values of photon transverse momentum cut and top-quark charge on the K-factor. Our numerical results show that the K-factor is not very sensitive to both the transverse momentum cut of photon ($p_{T,cut}^{(\gamma)}$) and the top-quark electric charge (q_t). The K-factor variation is about 3%, when we change q_t from $2e/3$ to $-4e/3$. But the $p_{T,cut}^{(\gamma)}$ and q_t impact the total integrated cross sections obviously.

Acknowledgments: This work was supported in part by the National Natural Science Foundation of China (No.10875112, No.11075150, No.11005101), and the Specialized Research Fund for the Doctoral Program of Higher Education (No.20093402110030).

[1] Abe F, *et al.* (CDF Collaboration) 1995 Phys. Rev. Lett. **74** 2626

[2] Abachi S, *et al.* (DØ Collaboration) 1995 Phys. Rev. Lett. **74** 2632

[3] Chang D, Chang W F and Ma E 1998 Phys. Rev. **D59** 091503

[4] Abazov V M, *et al.* (D0 Collaboration) 2007 Phys. Rev. Lett. **98** 041801

[5] Baur U, Buice M and Orr L H 2001 Phys. Rev. **D64** 094019

[6] Nason P, Dawson S and Ellis R K 1988 Nucl. Phys. **B303** 607; Beenakker W, Kuijf H, van Neerven W L and Smith J 1989 Phys. Rev. **D40** 54

[7] Melnikov K and Schulze M 2009 JHEP **08** 049; Czakon M and Mitov A, Nucl. Phys. **B824** (2010) 111

[8] Korner J G, Merebashvili Z and Rogal M 2008 Phys. Rev. **D77** 094011; Czakon M 2008 Phys. Lett. **B664** 307; Bonciani R, Ferroglia A, Gehrmann T, Maitre D and Studerus C 2008 JHEP **07** 129; Anastasiou C and Aybat S M 2008 Phys. Rev. **D78** 114006

[9] Bonciani R, Ferroglia A, Gehrmann T and Studerus C 2009 JHEP **08** 067; Beneke M, Falgari P and Schwinn C 2010 Nucl. Phys. **B828** 69; Czakon M, Mitov A and Sterman G F 2009 Phys. Rev. **D80** 074017

[10] Beenakker W, *et al.* 2001 Phys. Rev. Lett. **87** 201805; Reina L and Dawson S 2001 Phys. Rev. Lett. **87** 201804

[11] Dittmaier S, Uwer P and Weinzierl S 2007 Phys. Rev. Lett. **98** 262002; Melnikov K and Schulze M 2010 Nucl. Phys. **B840** 129

[12] Lazopoulos A, McElmurry T, Melnikov K and Petriello F 2008 Phys. Lett. **B666** 62

[13] Duan P F, Ma W G, Zhang R Y, Han L, Guo L and Wang S M 2009 Phys. Rev.**D80**, 014022

[14] Melnikov K, Scharf A and Schulze M Phys. Rev.**D83** 074013

[15] Private communications between Fleck I and authors

[16] Hahn T 2001 Comput. Phys. Commun. **140** 418

[17] Hahn T and Perez-Victoria M 1999 Comput. Phys. Commun. **118** 153

[18] Harris B W and Owens J F 2002 Phys. Rev. **D65** 094032

[19] Amsler C, *et al.* 2008 Phys. Lett. **B667** 1

[20] Frixione S 1998 Phys. Lett. **B429** 369